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Impacts of Riprapping to Ecosystem Functioning, Lower Sacramento River, California

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Summary: *Like many large rivers, the lower Sacramento River exhibits fragmentation and disconnection from ecological processes. Much of the degradation results from river meandering and erosion being halted by rock riprap bank protection. Over half (more in certain reaches) of the river's banks within the lower 194 miles have been riprapped, mainly from 4 decades of work by the Corps of Engineers' Sacramento River Bank Protection Project (SRBPP). While the SRBPP causes both site-level (habitat structure) and reach-level (ecosystems) impacts, compensatory mitigation is currently directed at only site-level impacts. Most reach-level impacts, such as reductions of (a) food-chain production, (b) sediment and organic material storage, and (c) formation of new "accreted" habitats, are complex, relatively poorly understood and unaddressed in current mitigation programs. However, another reach-level impact, reduction of large woody (in-stream) debris (LWD) functioning is much better understood and is clearly negatively impacting fish and wildlife resources. LWD is widely important to fish and, under unimpaired conditions, very long-lived. LWD has key roles in physical habitat formation, sediment and organic-matter storage, and in maintaining both essential habitat complexity and refugia. Losses of LWD reduce both habitat quality and carrying capacity. As in other northwestern U. S. rivers, LWD of the lower Sacramento River is highly important to juvenile salmonids, including three federally listed species; it is also part of essential habitat for the federally listed Sacramento splittail. Riprapping prevents the recruitment of new LWD along the armored banks, and it reduces the retention of LWD inputted from non-armored areas. The cumulative loss of LWD functioning for the lower river is now at least 67-90 percent, or more, compared to pre-SRBPP conditions. The use of set-back levees to achieve bank protection goals offers the best mitigation solution. Set-back levees allow both site- and reach-level impacts to be fully avoided, and they maximize habitat enhancement opportunities. Large-scale rehabilitation of the river with set-back levees is also needed, given the large impacts of past riprapping and large monetary sums now being spent for fisheries restoration. Development of statistical models describing LWD and general ecosystems functioning for the lower river is crucial to ensure future reach-level impacts are fully identified and offset. In the interim, compensatory mitigation attempted where set-back levees are infeasible must consider all site- and reach-level losses, including LWD functioning losses; and the compensatory mitigation features used must be guaranteed to function for the full design life of the bank protection work.*

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INTRODUCTION AND BACKGROUND

This report pertains to bank protection (riprapping) along the lower Sacramento River downstream of Red Bluff Diversion Dam, performed mainly under auspices of the Corps of Engineers' (Corps') Sacramento River Bank Protection Project (SRBPP). Since initial authorization in 1960, two phases of the SRBPP have resulted in riprapping of 152 miles of riverbank. About 6 miles more work is being planned for implementation under existing authority.

When existing authority expires, prospects are uncertain for reauthorization of the SRBPP in its current form. However, it is likely that some form of bank protection program or project will be continued on the Sacramento River for the foreseeable future. Therefore, the issues, problems and potential solutions raised herein should have long-term relevancy and consequences.

As with many other public works projects that have operated continuously for decades, environmental mitigation for the SRBPP has undergone a radical evolution. The first phase, encompassing about 81 miles of bank protection from 1960 to 1975, had no environmental mitigation. However, Congress later (1986) approved a post-project mitigation program involving the purchase, protection, and revegetation of 260 acres[1] of riparian lands and habitat. Implementation of this program was recently completed.

When the second (77-mile) phase of SRBPP began in 1976, mitigation for individual construction contracts (a group of several bank protection sites) consisted solely of environmental easements and rock fill. The easements, designated "Right 8s," were acquired where water-side berms (relatively flat, bench-like projections of earthen material extending from the levee) at least 30 feet in width existed. Easements compensated landowners to preserve, consistent with flood control and maintenance standards, natural riparian vegetation on the berm. Rock fill (usually a smaller version of the standard quarry rock used in riprap blankets) was considered an environmental mitigation feature by the Corps because it "protected" existing berm and levee vegetation from further losses due to erosion. Thus, for several years, up to 75 percent of project costs for rock fill were designated "environmental costs" by the Corps. However, an initial follow-up study by the U. S. Fish and Wildlife Service (Service) in 1987 (DeHaven and Michny 1987) found that Right 8 easements and rock fill had been exorbitantly expensive and largely ineffective in meeting intended environmental objectives. A subsequent follow-up by the Service in 1992 (USFWS 1992a) documented the failures persisting.

During later stages of second phase SRBPP work, compensatory mitigation needs were gradually determined through habitat-based assessments. The Corps began to provide a broader suite of mitigation measures, including, beginning in 1989, riparian revegetation efforts on berm areas.

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[1]This figure was recommended by the Corps; the resource agencies had determined that 640 acres were needed as compensation.

Also, several experimental mitigation features were implemented, including gravel and rock near-shore benches for offsetting impacts to juvenile salmonid rearing habitat, and vertical, earthen banks constructed for offsetting losses of bank swallow nesting substrates. These were mostly small-scale, "demonstration" efforts. Most of these early habitat-based mitigation efforts and experiments were also found by the Service to be unsuccessful or marginally successful (USFWS 1991).

Since the early 1990s, habitat-based analyses of impacts and mitigation needs for SRBPP work have been further refined and improved. The Corps has recently begun addressing both the environmental requirements of several listed species[2] associated with the Sacramento River (and affected by the project) and providing compensation for general fish and wildlife habitat impacts. Compensation needs for general impacts to habitat have been based largely on evaluations done using the Service's Habitat Evaluation Procedures (HEP). However, this recent reliance on HEP is causing a dilemma which forms part of the impetus for this report.

The dilemma relates to two earlier actions by the Service in the early 1990s. First, in October 1992, Shaded Riverine Aquatic (SRA) Cover[3] of the Sacramento River system was designated as high value, unique, and irreplaceable habitat (i.e, Resource Category 1)[4] relative to SRBPP work (USFWS 1992b). Then, the following year, the Service produced a draft Habitat Suitability Index (HSI) model for SRA Cover (Fris and DeHaven 1993), for use in impact analyses with HEP.

Because it was considered the best tool currently available, the HSI model for SRA Cover has been used for aquatic impact (and mitigation options) analyses for several recent SRBPP contracts. However, the Service developed the SRA Cover model specifically for application to areas of SRA Cover meeting the Service's classic definition[3] of this habitat. The model was not designed for assessing impacts or compensation values along riprapped banks which do not meet this definition. Specifically, the model was not designed for assessing the SRA Cover compensatory value provided by rock groins, hardpoints, shoreline scallops, boulders, vegetation plantings, or other similar mitigation features placed along rock riprapped banks, because the aquatic area adjacent to such banks is not, by definition, considered true SRA Cover. (Also, SRA Cover impacted by the SRBPP is still being considered irreplaceable by the Service.)

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[2] i.e., Pursuant to section 7 of the Federal Endangered Species Act of 1973, as amended. Several listed fish species are discussed later herein.

[3] The Service has defined SRA Cover as the near-shore aquatic area occurring at the interface of the river and adjacent woody riparian habitat, where the river bank is composed of eroding, earthen substrate supporting riparian vegetation which overhangs and/or protrudes into the water, and the water may contain woody debris, including logs, branches, leaves, and roots, as well as variable depths, velocities and currents.

[4] i.e., Pursuant to the Service's Mitigation Policy, as published in the Federal Register, Vol. 46, No. 15, January 23, 1981. Under this Policy, the Service recommends that all losses of existing Resource Category 1 habitat be prevented, as these one-of-a-kind areas cannot be replaced. Only insignificant changes that do not result in adverse impacts to habitat value may be acceptable, provided they have no significant cumulative impact.

An analysis contrary to this position has, in fact, been recently done by the Service for SRBPP work along the lower American River, a tributary to the lower Sacramento River. In this case, however, the Service recognized that because of dense infrastructure, the use of set-back levees (which allow existing SRA Cover to remain intact) was not a realistic project alternative. Thus, the Service employed the SRA Cover model with recognition that it was the best tool available and would help ensure replacement of *most* structural habitat components of SRA Cover being impacted. The Service cautioned, however, that the impacts of the bank protection to ecosystem functions and processes could *not* be properly addressed with the existing SRA Cover model (USFWS 1998a). Moreover, this position had been stated as early as 1993 (USFWS 1993a).

These events lead to the present dilemma. The Corps is currently proposing another contract (42E) of the SRBPP which would entail construction at up to six sites totaling about 3,100 Linear Feet (LF) of bank between RMs (River Mile) 85 and 164 along the lower Sacramento River. The Corps engaged a consultant to provide a HEP evaluation of impacts and mitigation needs for both riparian habitat and SRA Cover (Jones & Stokes 1999). The Service has been a participant on the consultant's HEP team, and generally concurs with the findings of the riparian habitat portion of the HEP application.

However, the consultant's HEP approach to the SRA Cover portion of the evaluation generally mirrors the recent HEP done by the Service for the lower American River work. The Service finds such an approach[5] inadequate, because it fails to fully address all of the project's impacts to ecosystem functioning of the river.

To understand the basis for this conclusion, a thorough discussion of ecosystem functioning and impacts related to riprapping along the lower Sacramento River is essential. Accordingly, this report has been prepared in which the primary objectives are to:

1. Describe in general terms the known impacts to ecosystem functions and processes of the lower Sacramento River which result from traditional riprapping;

2. Describe in detail one of the most important and best understood of these ecosystems impacts–loss of large woody debris (LWD) functioning–particularly as it relates to key fishes of the lower Sacramento River;

3. Estimate the cumulative total loss of LWD functioning that has occurred due to riprapping of the lower Sacramento River;

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[5]The latest versions of the consultant's reports have increasingly incorporated certain HEP modifications designed to begin addressing the ecosystem-functioning loss issue. However, the Service finds that the changes made still fall short of fully addressing all impacts to the river's ecosystem functioning.

4. Support the first three objectives with pertinent published and unpublished literature; and

5. Present appropriate conclusions and recommendations for future Service (and other involved agency) action.

GENERAL IMPACTS TO ECOSYSTEM FUNCTIONING

A review of historical conditions on the Sacramento River can facilitate an understanding of how the river formerly functioned, and suggest the ecological functions and processes that were essential to development of such an abundant and rich array of fish and wildlife resources. However, clearly defining historical conditions is somewhat problematic, since most of the more detailed quantitative and qualitative descriptions of the Sacramento River occurred during or after major episodes of human impact. Nevertheless, we can broadly surmise about how the pre-settlement Sacramento River appeared.

The river at this time was free-flowing, without the restrictions of dams and diversions. Flows varied dramatically. Late summer flows were low in contrast to today's summer flows, probably averaging about 3,000 cubic feet per second (cfs), with dry year flows dropping to perhaps about 1,000 cfs. Flows fluctuated widely in response to winter rains, and sustained high flows occurred in the spring in response to snow melt.

The higher flow events resulted in over-bank flooding, often over extensive reaches of the valley floor. Overflow areas were covered by dense forests of riparian vegetation. Some accounts place the riparian band as extending up to 4-5 miles along each side of the river and encompassing at least one-half million acres. Extensive swamps, marshes, and other diverse and expansive wetlands were also nourished by the regular flooding events.

Bank erosion and river meander, the basic forces for most riverine ecological processes and functions, were unimpeded. Erosion was most active on the outsides of the numerous meander bends, where the highest velocities impinged directly on the earthen substrates. As one bank was eroded, the opposite bank experienced sediment accretion. Some of the meanders became cut-off from the river, forming oxbow lakes and other broad, highly diverse channel overflow areas. Erosion also resulted in the input of large volumes of woody debris of a broad range of sizes, types, and complexities into the river. The fish, wildlife, and riparian vegetation of the river were in a dynamic equilibrium, adjusted to, and dependent upon the cycle of erosion, deposition, and changing channel pattern as the river slowly swung back and forth across its meander belt. The ecological health and productivity of the river at any point in time was dependent on periodic rejuvenation associated with these natural processes and changes.

From this pristine, pre-settlement picture of the river, jump forward 150 years to the present era. The most significant environmental changes and impacts have now occurred. The extensive riparian forests and wetlands have been largely removed. The devastating environmental impacts wrought by the search for gold have been felt. The river is now highly controlled by dozens of dams on the main stem and tributaries, largely confined by levees, and overall, a mere remnant of the ecologically dynamic and complex system of the past.

Nevertheless, even in today's highly modified system, erosion remains a key element to the rivers's overall ecological health. Wherever remnants of river meandering, or even less obvious erosion, still occurs, the river's basic ecological functions and processes continue. The relative amount of erosion and its resultant affects on channel meander, point bar build-up, and other sedimentation features diminishes sharply proceeding down the river from Ordbend to Collinsville, a distance of about 185 RMs, and the current focus area of the SRBPP.

From Ordbend downstream to Colusa (RMs 185-143; hereafter, **Reach 3**), the river is generally bordered by set-back levees (except for the uppermost 8 miles of the right bank, which is a non-set-back levee) and berms up to several hundred feet in width where the river is free to erode, meander, and accrete in a semi-natural manner. Some oxbows and overflow areas still occur. Point bars, islands, high and low terraces, in-stream woody cover, early successional riparian plant growth, and other evidence of river meander and erosion are common. Such important habitat features are still fairly well-distributed throughout the reach, although some areas of clumping and fragmentation occur. This reach has a moderate amount of bank protection already installed (*see* Cumulative Bank Protection section). While far from its pristine condition, this is clearly the most ecologically functional reach of the three reaches where bank protection activity is focused.

From Colusa downstream to Verona (RMs 143-80; hereafter, **Reach 2**) where the river joins with the Feather River, levees are generally constructed near the river's edge. Severe long-term riparian vegetation losses have occurred in this reach. A narrow berm is sometimes present, affording some erodible substrate, but erosion and deposition processes, while significant, are nonetheless greatly diminished compared to Reach 3. Also, there are both more and larger gaps within this reach without the presence of important habitat features, due to the greater amount of riprap in place than in Reach 3.

From Verona downstream to Collinsville (RMs 80-0; hereafter, **Reach 1**) at the confluence with the San Joaquin River, the river is even more narrowly constrained (except in the last few miles) by levees. Most of this reach is also influenced by tidal action during much of the year. Ecological processes and functioning in this tidal reach may be much different than in the two non-tidal reaches (2 and 3), although to date, this issue has not been adequately addressed in the existing literature pertaining to the lower Sacramento River.

Nevertheless, Reach 1 (tidal reach) is clearly the most ecologically degraded of the three river reaches which have been impacted by bank protection and riprapping. There have been huge losses of riparian and wetland resources, and today little, if any, berm or bank substrates remain where erosion can still occur. This is mainly due to a large proportion of the levees in Reach 1 now having been riprapped under auspices of the SRBPP and other authorities. Also, in contrast with Reaches 2 and 3, the primary source of much of the limited erosion that does still occur within Reach 1 is wave-wash from vessels and wind, rather than erosion due to high-velocity flood flows.

From this brief picture of the three lower Sacramento River reaches, we can move to examination of how just one aspect of typical bank protection–riprapping with quarry rock–affects natural river functions and processes. Such riprapping has been shown to:

- Reduce recruitment of spawning gravel for salmonids (DWR 1994). This is less of an issue in recent years than earlier, because most SRBPP work is now focused on reaches downstream of significant spawning areas. However, past SRBPP impacts, when work occurred farther upstream, and earlier Corps riprapping work from Chico Landing upstream to Red Bluff (under the Corps' Sacramento River, Chico Landing to Red Bluff Project), were found to have significantly impacted spawning gravel recruitment to the river's lowermost spawning areas;

- Halt new accretion of point bars and other depositions where new riparian vegetation can colonize (DWR 1994);

- Arrest meander migration (DWR 1994), which over time, reduces habitat renewal, diversity and complexity (NRC 1996);

- Incise the thalweg of the river adjacent to the armored area (DWR 1994; NRC 1996), while narrowing the low-flow channel width (DWR 1994). Both changes result in decreased hydrological and biological diversity;

- Create a relatively smooth, "hydraulically efficient" surface along the riprap blanket, which is contrary to the habitat requirements of native fishes, including salmonids, for hydrodynamic complexity (Lister et al. 1995; NRC 1996);

- Fill in sloughs, tributary channels, and oxbow lake areas, causing loss of nearby wetland habitat and diversity (DWR 1994);

- Limit lateral mobility of the channel, thus decreasing general habitat complexity of the near-shore aquatic area (Sedell et al. 1990; NRC 1996), and reducing complex lateral habitats, including small backwaters and eddies (Gregory et al. 1991; Bisson et al. 1987).

  This removes numerous and important refugia for plants, invertebrates, fish, birds, and mammals (Welcomme 1979);

- Decrease near-shore roughness, causing stream power (i.e., velocities) to increase more rapidly with increasing discharge (Sedell et al. 1990), thus often eliminating critical refugia areas for fish and aquatic organisms during high flows (Gregory el al. 1991) and causing accelerated erosion at the downstream interface between the riprapped section and adjacent earthen section. This in effect results in riprap necessitating the need for more riprap.

- Halt erosion and reduce habitat complexity, thus reducing the ability of near-shore areas to retain sediments and organic materials, and to determine the quantity of organic inputs (Gregory et al. 1991; Sedell et al. 1990). Critical stream refugia areas are also lost due to the isolation of the river from its watershed, primarily by uncoupling the biotic and hydrologic interaction between the stream and the riparian zone (Sedell et al. 1990);

- Impede plant growth through thick rock at the waterline, which results in vegetation being farther back from the shoreline, thus reducing the contribution of allochthonous (produced outside the stream ecosystem) food resources for aquatic invertebrates (Murphy and Meehan 1991); and

- Halt erosion, which stops woody vegetation from falling into the river, thus causing a long-term reduction in the recruitment of new large woody debris to the system (Hicks et al. 1991), with a resulting wide range of negative effects (*see* the detailed discussion with supporting references which follow).

This is merely a brief summary of some of the more obvious direct effects of riprapping. There are hundreds of additional scientific studies that are pertinent to the discussion. These studies have been conducted on rivers throughout the U. S. and elsewhere, providing substantial indirect evidence of the wide range of deleterious effects of bank protection on the lower Sacramento River.

Most of the pertinent related literature is concerned with either (1) the effects of bank stabilization or channelization on rivers, or (2) the effects of snagging and clearing operations. In 1980, the Service published an annotated bibliography (Stern et al. 1980a) and synthesis (Stern et al. 1980b) of the effects of bank stabilization on the physical and chemical characteristics of streams and rivers, based on 213 published references. The Service (Marzolf and Benson 1980) and others (e.g., Shields and Nunnally 1984) have also published literature reviews of environmental effects of snagging and clearing on stream ecosystems. These earlier reviews were themselves reviewed and summarized in a 1989 report by the Service for the Sacramento District of the Corps (DeHaven 1989).

LARGE WOODY DEBRIS: IMPORTANCE AND IMPACTS

Over the last two decades, aquatic ecologists, hydrologists, and geomorphologists have begun to recognize and describe the high importance of large woody debris (LWD)[6] in ecosystems of forested streams[7] (e.g.,

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[6]Hereafter, LWD is generally meant to describe fallen riparian wood pieces that exhibit both large size (e.g., often >15 feet in length or >18 inches in diameter) and high complexity, such as occurs when an entire mature tree, including root mass, is undermined by erosion and falls into the river.

[7]Streams are classified by their "order." Headwater stream channels are designated first-order; two first-order streams combine to form a second-order stream. Two second-order streams combine to form a third-order, and so forth. Thus "stream" is used interchangeably with "river," and may refer to the Sacramento River.

Sedell et al. 1988; Sedell et al. 1990; Dolloff 1994; Gurnell et al. 1995)[8]. Perhaps no other structural component of the environment is as important to salmon habitat as is LWD (NRC 1996). Numerous reviews of the biological role of LWD in streams of the Pacific Northwest have concluded that it plays a key role in physical habitat formation, sediment and organic-matter storage, and in maintaining a high degree of spatial heterogeneity (i.e., habitat complexity) in stream channels (e.g., NRC 1996; Hicks et al. 1991; Sedell et al. 1990; Reeves et al. 1991; Bisson et al. 1987). The loss of LWD from streams usually diminishes habitat quality and reduces carrying capacity for rearing salmon during all or part of the year (NRC 1996; Dolloff 1994; Sedell et al. 1990; Hicks et al. 1991). Moreover, the importance of LWD to fish habitat has been established for all sizes of streams (Bisson et al. 1987; Dolloff 1994). As a stream channel becomes too wide for spanning by large logs and downed trees, the debris is deposited along the channel margin, where it often forms the most productive fish habitat in main stem rivers (Bisson et al. 1987; Gregory at al. 1991).

It is believed that most large, main stem rivers and estuaries historically had great amounts of LWD (Gonor et al. 1988), with a frequency of snags likely in the same order of magnitude as the frequency of LWD and downed trees in intermediate-sized streams (Harmon et al. 1986); many biologists and engineers are unaware of this significant historical frequency of snags and LWD in large rivers (Sedell et al. 1990).

Ironically, throughout North America, people systematically cleaned such downed trees and LWD from streams for more than 150 years (Sedell et al. 1988). The great ecological value of such organic debris was not yet known (Sedell et al. 1988). The Sacramento River was no exception. A conservative estimate is that from 1867 through 1912, 91 snags per km were removed from 368 km of the main stem Sacramento River for navigation improvement (Sedell et al. 1990). One may surmise that based on this number, the actual number of snags per km may have been in the hundreds, although there is little hard evidence upon which to base such speculation. What is more certain, however, is that the river undoubtedly experienced a massive decline of LWD, as snagging and clearing was done, huge areas of riparian forest were removed, and the river was gradually leveed and dammed. These impacts to LWD were then further exacerbated by gradual riprapping of the levees.

SACRAMENTO RIVER--EVIDENCE OF IMPORTANCE TO SALMONIDS

Over the past 2 decades, a number of studies have consistently substantiated, indirectly if not directly, the high value and importance of in-stream wood and LWD to salmonids of the Sacramento River. The evidence has often been indirect, because none of the past studies were designed to specifically examine effects of LWD alone on salmonids. Instead, most research has involved comparisons of salmonid numbers and densities along natural, earthen river banks versus riprapped banks. In-stream wood, including LWD, along with overhead woody cover, and variable depths and velocities (i.e., SRA Cover), are generally

[8] Throughout this section, due to the large volume of pertinent literature, primarily review-type references have been cited; these reviews cite additional literature pertinent to most points. The reader is directed to these for further documentation.

prominent components of the near-shore aquatic zone along such natural, earthen banks.

The California Department of Fish and Game (CDFG) was among the first to examine the issue quantitatively. In a Corps-funded study, with field work done from Red Bluff downstream to Ordbend during 1981, they found substantial variability and thus no statistical differences in the total quantity of invertebrates collected by drift nets placed along riprapped versus natural banks. However, based on daytime electrofishing results at three of the paired (riprapped versus natural) sampling locations, juvenile salmonid densities along riprapped banks were only about one-third as large as along corresponding natural banks (many of which had fallen trees or exposed tree roots in the water), and the difference was statistically significant for two of the three paired comparisons (Schaffter et al. 1983). The authors concluded that traditional bank protection of the SRBPP, if continued, would likely cause reduced salmonid survival (Schaffter et al. 1983).

Subsequently, the Service has conducted a series of similar studies, primarily also based on daytime electrofishing results, which have provided consistent confirmation of the earlier CDFG findings. For example, a 1988 study by the Service of proposed bank protection sites and control (similar, but not planned for bank protection) sites within the Butte Basin reach from RMs 187-192, found the highest juvenile salmonid values (catch/unit of effort=CPU) associated with near-shore areas characterized by "woody material, sloping banks, and moderate velocities" (Michny 1988a). The bank protection work at the proposed sites, which included some experimental "gravel fish groins" and "rock fish groins" for fisheries mitigation, was then done, and both treated and control sites were followed for another 3 years. Juvenile salmonid CPUs were consistently: lowest at the riprapped sites; highest at the natural bank sites (with one exception), which had areas of overhead and in-stream woody cover; and intermediate at the experimental mitigation sites (USFWS 1992c).

From 1984 through 1987, a similar study was conducted by the Service at several sites in the Chico Landing to Red Bluff reach between RMs 240 and 243. Two mitigation measures consisting of a "5:1 gravel covered fish slope" and "a gravel covered riprap" site were compared to standard riprap and natural banks. The evaluation again focused on juvenile salmonid CPUs as measured by daytime electrofishing. The study results (four annual reports) followed closely the findings from the Butte Basin juvenile salmon study, confirming the low value of riprapped banks, high value of natural banks (with various degrees of in-stream and overhead woody cover), and intermediate value of the two mitigation sites (Michny and Hampton 1984; Michny and Deibel 1986; Michny 1987a; and Michny 1989).

Another pertinent study by the Service was related to an evaluation of the effects on salmonid rearing habitat of an experimental method of bank protection–a palisades.[9] Several study sites were located in the vicinity of Woodson Bridge, between RMs 217 and 219; both pre-and post-construction monitoring via

[9]The method consists of placing a heavy webbing mesh made of nylon, which is vertically attached to wooden pilings, along the eroding bank. The structure is designed to reduce velocities, trap sediment, and thereby halt the bank erosion.

daytime electrofishing CPUs was completed. Pre-construction results from 1985 and 1986 sampling showed (a) lowest juvenile salmonid CPU along riprapped banks, (b) highest CPU along natural banks, and (c) among the natural bank sites, the highest CPU at a site with extensive riparian and in-stream woody vegetation (Michny 1987b). Post-construction sampling in 1987 and 1988 showed a continuation of the pre-construction trends, plus an indication that the palisades approach was, for salmonids at least, environmentally superior to standard riprap bank protection, but still substantially less valuable than natural banks with riparian vegetation and in-stream wood (Michny 1987c; Michny 1988b).

In 1989 and 1990, another similar study was conducted by the Service between RM 90 near Knight's Landing and RM 101 near Tyndall Landing. Again, CPUs of juvenile salmonids were determined from daytime electrofishing effort. This time, a total of 16 sampling sites were established: eight standard riprapped sites–four with cobble and four with quarry rock; four natural bank (construction) sites where standard riprap was proposed; and four other natural (control) banks with features similar to the planned work sites. Findings in this case were mixed: the 1990 data showed the usual clear preference of salmonids for the natural banks compared to both types of riprap, but the 1989 results deviated, with slightly higher salmonid densities being recorded on natural control and cobble riprapped sites than on natural work sites and quarry-rocked sites (Harrison 1990). However, results may have been confounded by small sample sizes and drought conditions which resulted in relatively small numbers of salmon being captured.

Finally, a more recent confirmation of the high value of SRA Cover and its various attributes, including in-stream wood, to juvenile salmonids, comes from the Service's 7-year Anadromous Fish Doubling Plan Instream Flow Investigations, which began in February 1995. One recently completed phase of this study involved the derivation of Habitat Suitability Indexes (HSIs) for juvenile chinook salmon rearing in the upper Sacramento River. The study area extended from the Anderson-Cottonwood Irrigation District Diversion Dam at RM 298 downstream to Battle Creek at RM 271. Extensive near-shore observations of juvenile salmonids were made by divers using snorkeling gear. Fish were enumerated in relation to near-shore cover types. These snorkeling results were consistent with the findings of the numerous previous electrofishing results. Based on numbers of fish observed, the lowest HSI was for riprapped sites–0.01(on a scale of 0.00 to 1.00), while in contrast, HSIs of sites with some combination of in-stream and overhead woody cover ranged from 0.63 (fine, in-stream woody vegetation, plus overhead cover) to 1.00 (log >1 foot diameter, plus overhead cover) (USFWS 1997). The total amount of sampling done in this study was quite large–16 sections of bank at each of 30 sites each week for 12 weeks over a 9-month period. From this large effort, many of the comparisons of universally low salmonid values at riprapped banks versus other bank types with various forms of woody cover were found to be statistically significant (USFWS 1998b).

These findings for salmonids on the lower Sacramento River are inferentially supported by dozens of other studies of salmonids, including much recent work, conducted throughout the world. For example, on a small coho salmon stream in coastal Washington, the experimental addition of LWD resulted in significant increases of winter populations of juvenile coho, and a significant increase of coho smolt yield from the treated reaches (Cederholm et al. 1997). In Sweden, a study of brown trout revealed that artificial addition of woody debris to habitat resulted in the fish having less swimming activity, less aggression, and less feeding activity, indicating that the presence of the wood reduced intraspecific competition through visual isolation, thus allowing fish to reduce aggressive interactions and energy expenditures (Sundbaum and Naslund 1998). In Japan, woody debris was found to be positively correlated with juvenile masu salmon densities and to provide important microhabitat for the species (Inoue and Nakano 1998). In a creek in Canada, the addition of wooden structures which simulated fine woody debris significantly increased both density and biomass of rainbow trout, presumably because the woody debris provided structurally complex habitat served as a refuge from predators and as sites from which foraging forays were staged (Culp et al. 1996). In the Appalachian Mountains of North Carolina, a stream with a large amount of LWD supported higher density and biomass of trout (rainbow, brown, and brook) than a comparable stream with a low amount of LWD (Flebbe and Dolloff 1995).

The consistent findings of the high importance of in-stream wood and LWD (and associated natural river banks) to juvenile salmonids worldwide and on the Sacramento River in particular has special significance in light of the growing number of federally listed salmonid species which now occur in the Sacramento River. The river's winter-run chinook salmon Ecological Significant Unit (ESU) was the first to be listed (Endangered) in 1989. Then, in 1997, the Central Valley steelhead ESU was listed (threatened). Most recently, in 1999, the Central Valley spring-run chinook salmon ESU was listed (threatened), while Central Valley fall/late fall run chinook salmon ESUs were determined to not warrant listing yet, but were relegated to "candidate" status. The river's federally listed salmonids occur throughout all three river reaches (i.e., Reaches 1-3) of the current SRBPP focus area. (Note: Because these species are anadromous, listing responsibility falls under purview of the National Marine Fisheries Service.)

Today, significant restoration programs for the river's anadromous fish are in progress from two primary venues: the Central Valley Project Improvement Act (CVPIA) and CALFED. The CVPIA provides for additional Central Valley Project water for fish and wildlife and a funding mechanism to support immediate actions aimed at a long-term goal of doubling natural production of anadromous fish in Central Valley streams. CALFED is a broad consortium of Federal and State resource agencies mandated by the Bay-Delta Accord with broad objectives of restoring the San Francisco Bay-Delta resources, and their tributary streams. Together, these efforts are directing hundreds of millions of dollars at restoration efforts. It is incongruous and unacceptable that, while such massive restoration effort is underway, 4 decades worth of riprapping impacts to lower Sacramento River ecosystems functioning remain largely unmitigated and are, in fact, continuing to accrue from additional riprapping work.

OTHER RECENT EVIDENCE OF IMPORTANCE TO SALMONIDS

Investigations similar to the above studies done by the Service along the Sacramento River are beginning to emerge from other areas of the Pacific Northwest. Two recent studies in particular are of significance and merit discussion here because they involved large sampling effort which conferred statistical significance to many of the findings:

Study 1. One recent study by a Corps (Seattle District) consultant involved the main stem Skagit River in northwest Washington (Beamer and Henderson 1998). This river contains four salmonid species: chinook, coho, and chum salmon, and rainbow trout. Sampling by electrofishing was done at natural bank sites and various "hydromodified" (i.e., bank protection) sites along an 80-mile reach of river.

Both juvenile chinook and coho were found to be positively correlated in abundance with amount of in-stream wood cover; this variable explained 82 percent of chinook variation. Also, for all species and age classes except sub-yearling chum, greater abundance occurred in complex rootwad type of cover than in simple, single-log cover. In addition, hydromodified banks with similar amounts of wood cover as natural banks tended to still support lower chinook abundances, likely because of less complexity of wood cover types (i.e., single logs/branches versus rootwads, debris piles, and other complex wood structures along natural banks). Furthermore, during low flows, the amount of in-stream wood along hydromodified banks was found to be less than along natural banks (Beamer and Henderson 1998).

Another impact suggested by the authors was a possible lowering of the "wetted width of bank habitat" along hydromodified banks, assuming that the hydromodified banks are hydraulically smoother and thus have a narrower low-velocity "edge" (Beamer and Henderson 1998).

The authors concluded that traditional bank protection in the study reach has dramatic adverse impacts on all juvenile salmonids except rainbow trout. They also concluded that employing natural cover-types in association with traditional bank protection did not fully compensate for the site-level losses and did nothing to offset reach-level losses. Reach-level losses, which include the loss of wood recruitment and retention processes, changed the habitat characteristics of the entire river reach (Beamer and Henderson 1998).

The authors added that the negative impacts of bank protection may have been underestimated in their study, because electrofishing likely underestimates fish numbers associated with natural bank habitat (Beamer and Henderson 1998). This finding also has significance to the numerous studies done by the Service with electrofishing (and discussed above) along the Sacramento River.

Study 2. Another pertinent study was recently conducted by the Service's Western Washington Office in Lacey, Washington (Peters et al. 1998). Sampling was done at 67 sites along 15 different rivers in western Washington. Juvenile salmonids were enumerated during both day and night snorkel surveys. Five kinds of bank protection projects, based on their physical form, were evaluated and compared with unprotected control sites.

Among the findings were that: (a) traditional riprap bank protection sites had lower fish densities than controls during all seasons; (b) in-stream LWD cover and overhead riparian stream cover were the variables most consistently influencing fish densities at both stabilized (i.e, bank-protected) and control sites; (c) during spring and summer, fish densities were positively correlated with LWD surface areas; (d) during spring, summer, and winter, bank protection accomplished with LWD (i.e., a layer of LWD either buried or cabled into the bank) resulted in higher fish densities than control sites; and (e) LWD put into continuous revetment reaches did not increase overall fish densities (Peters et al. 1998).

The results also supported the findings of previous studies showing that the impacts to salmonids of bank protection vary seasonally. Also, as in Study 1 above, the authors concluded that the findings of impacts along stabilized sites may have been conservative (Peters et al.1998).

IMPORTANCE TO OTHER LISTED FISHES OF THE SACRAMENTO RIVER

Two other federally listed fish, delta smelt and Sacramento splittail, also occur in the lower Sacramento River. Both species have habitat needs which include in-stream vegetative cover and other attributes often associated with earthen, vegetated river banks and levees.

Delta Smelt. The delta smelt was listed (threatened) by the Service in 1993. This species historically occurred from Suisun Bay at least upstream to the City of Sacramento on the Sacramento River, and to Mossdale on the San Joaquin River (Moyle et al. 1992). Recently, the species has been recorded as far upstream on the Sacramento River as Verona, about 10 miles upstream of Sacramento (*personal communication*, Michael Thabault, USFWS); this shows that the current range of this species includes at least all of Reach 1. Most delta smelt spawning, however, is still thought to occur in freshwater of dead-end sloughs and shallow edge-waters of channels in the western Delta and lower Sacramento River system (USFWS 1993b).

The delta smelt's adhesive, demersal eggs attach to hard substrates such as rocks, gravel, tree roots, and submerged branches (USFWS 1993b). The species' pelagic life history, dependence on pelagic microzooplankton, very short 1-year life span, and low fecundity are characteristics of a fish species that is affected greatly by perturbations to its reproductive habitat or larval nursery areas (USFWS 1993b).

Therefore, any activities which would adversely affect near-shore shallow water habitat within the species' range are considered potential threats to the species (USFWS 1999).

Sacramento Splittail. Sacramento splittail were listed (threatened) by the Service in 1999. This species is a silvery-gold member of the minnow family, which can grow up to 16 inches in length (USFWS 1999). In contrast to delta smelt, Sacramento splittail are relatively long-lived (up to 7 years) and highly fecund (up to 100,000 eggs per female; USFWS 1995).

Historically, splittail occupied habitat in lakes and rivers throughout the Central Valley (USFWS 1995), ranging upstream on the Sacramento River to at least Redding and upstream on the San Joaquin River to at least Millerton (Meng and Moyle 1995). Prior to 1995, it was generally believed that the distribution of the species had become largely confined to the Sacramento-San Joaquin Delta and estuary downstream of Sacramento (USFWS 1995; Moyle et al. 1989). However, since 1995, several years with improved hydrologic conditions, plus generally more intensive effort to sample for and record the species, have shown that the present distribution is wider than previously thought.

For example, current distribution extends to several upstream tributaries including the Mokelumne, Feather, and American rivers, as well as downstream areas, such as the Napa and Petaluma rivers (Sommer et al. 1997). Also, the species was recently recorded upstream on the Sacramento River at Red Bluff Diversion Dam and upstream on the San Joaquin River system at Fremont Ford, Salt Slough, and Mud Slough (Baxter 1999).

Splittail may thus still occur in most drainages within their historic range, although sampling records are insufficient to determine if all habitat below the first dam on each drainage is currently used (Sommer et al. 1997). Nevertheless, the Service maintains that habitat upstream to existing first dams is generally *potential* habitat, although relative abundance may currently be low in certain uppermost and fringe areas (*personal communication*, Michael Thabault, USFWS).

For spawning, splittail require shallow water areas, either fresh or brackish, with submerged vegetation. Such habitats are typically created by late winter and spring flooding of natural stream banks (USFWS 1999).

Splittail year-class strength has been positively correlated with freshwater outflow occurring during the species' late winter and spring spawning season (Meng and Moyle 1995; Sommer et al. 1997). One measure of outflow recently examined is the degree of inundation of Sacramento River flood control bypasses. In years of more extensive, lengthy flooding of such bypasses, splittail year-class recruitment increases (Meng and Moyle 1995; Sommer et al. 1997).

However, there has been no corollary evidence demonstrating that the increased overall production is due largely to the benefits derived from the flooded bypass habitat. Indeed, since bypasses are managed for flood control rather than fisheries, they are sometimes fish-unfriendly environs. Predation (e.g., by water birds) and water quality may at times be limiting factors for bypass habitat. Also, flow changes in bypasses can be both large and abrupt, thus fish stranding, particularly for juveniles, may at times be a problem. Also, stranding may be exacerbated within bypasses because of the proliferation of low-level levees associated with agriculture (most bypass areas are farmed during the dry season) and wildlife refuge lands.

The Service's view is that high splittail recruitment and eventual recovery of the species will likely be tied to maintenance of high-quality habitat along the main stem rivers and tributaries rather than the much more erratic and unpredictable habitat provided by bypass inundation. Habitat flooded along main river channels likely functions for splittail and other fishes over a much broader range of flows and conditions than bypass habitat. Thus, the abundant food for pre-spawning adults, spawning substrates, and larval rearing habitat for splittail tied to flooded vegetation (Sommer et al. 1997) may be much more important in main-channel than flood-bypass areas (*personal communication,* Michael Thabault, USFWS).

Woody debris is a highly important component of flooded riverine habitat. As such, it is also a highly important component of splittail habitat. Any activities which would affect woody debris or other aspects of near-shore shallow water habitat within the species' range are considered possible threats to the species (USFWS 1999).

HABITAT FORMATION AND CHANNEL GEOMETRY

Geomorphologists speak of LWD as "large structural roughness elements" or use similar descriptive phrases that refer to the ability of debris to control the flow of water in the stream channel. A classic example of such function was demonstrated in 1980 following the eruption of Mount St. Helens in Washington. A pyroclastic surge introduced huge volumes of wood and fine-grained sediment into a number of nearby streams. One of these, Clearwater Creek, became the subsequent focus of a multi-year LWD study of the effects of controlled debris removal (Lisle 1995). Debris removal caused additional scour and coarsening of the bed surface compared to segments with little or no debris removal. Total debris removal caused pools to become shallower and, in segments of low sinuosity, decreased the frequency of major pools. Overall habitat complexity also decreased after total debris removal (Lisle 1995).

In small streams such as Clearwater Creek, perhaps the single most important function of LWD in forming salmonid habitat is the creation of rearing pools. Single pieces of LWD or accumulations of smaller pieces anchored by a large piece often create a stepped longitudinal profile consisting of an upstream sediment deposit, the debris structure, and a downstream plunge pool (Bisson et al. 1987).

In addition to its role in pool formation, LWD provides habitat complexity, protecting fish from predation, excessive competition and physical displacement (Dolloff 1994). Fish in areas with complex cover have greater opportunities to be visually isolated, which may decrease the number of behavioral interactions and permit greater numbers of fish to coexist (Dolloff 1986). In smaller streams, such benefits may accrue across the stream cross-sectional area.

In large, main stem streams, such as the Sacramento River, the primary benefits of LWD switch to the channel margins, where the debris still acts to deflect and break up stream flow, often creating small eddies, pools, undercut banks, depth variability, and back-water areas that are used extensively by salmonids for rearing during various seasons (e.g., Murphy and Meehan 1991; Bisson et al. 1987; Gregory et al. 1991). In addition, sediment trapped and stored by debris further contributes to hydraulic and biologic complexity, especially in organically rich channels along low-gradient valley floor streams (Bisson et al. 1987). Moreover, there is no doubt that the presence of LWD induces increased physical habitat diversity in river channels of all sizes (Gurnell et al. 1995). Such habitat complexity benefits many free-swimming species, including trout and salmon, which require sites where food is plentiful and little effort is needed to hold a feeding position against the current (Sedell at al. 1988). Thus, most juvenile anadromous fish rearing in large rivers are concentrated along wood-rich stream edges (Sedell et al. 1988), whenever such edges are part of a given river's environment.

Furthermore, complex near-shore areas enhanced by wood provide a wide range of benefits to many other important fish and wildlife (Welcomme 1979), and are particulary critical as refuge areas during floods (Gregory et al. 1991; Dolloff 1994). During floods and other large-scale severe disturbances, LWD can diversify hydraulic forces and maintain structural complexity, thereby providing fish with important shelter areas (Shirvell 1990) and counteracting the tendency of the event to simplify the aquatic ecosystem (Lisle 1995). Such diversity and provision of refugia may be critically important along the lower Sacramento River, due to its extensive channelization and disconnection from historical floodplain where critical refuge and rearing habitat were formerly provided.

However, the preceding discussion is not meant to suggest that on large rivers, including the Sacramento, LWD has little or no function or benefit away from the river's margins. Indeed, even on the Sacramento, occasional trees or other large pieces of "captured" wood can be observed well away from shoreline areas. There are examples in Reaches 1, 2, and 3 where large pieces of mid-channel wood are known to have been stationary (or in some cases "growing" as the captured wood captures more wood) for at least the past 25 years (*personal observation*, compiler).

Also, in such large rivers, debris often provides essential salmonid habitat by "capping" side channels, and by causing scour holes, velocity breaks, and other habitat complexities in the shallower river braids (Murphy and Meehan 1991). Deposited debris is also capable of increasing channel width, producing mid-channel bars, and facilitating the development of meander cut-offs (Keller and Swanson 1979). Historically, logjams on pristine rivers created extensive secondary channels and off-channel sloughs and marshes, effectively increasing habitat complexity and total rearing area (Murphy and Meehan 1991), and the Sacramento River was no exception.

STORAGE OF SEDIMENT AND ORGANIC MATERIAL

LWD and other large roughness features of streams (e.g., boulders) create important storage areas for both inorganic sediment and organic material (Gregory et al. 1991; Bisson et al. 1987; Murphy and Meehan 1991). This is important, because to contribute habitat (inorganic sediment) or energy to the food web of a stream reach (organic matter) the material must first be retained in the channel where it can function and be processed (Murphy and Meehan 1991; Gregory et al. 1991; Bisson et al. 1987).

The stability and storage capacity of debris is enhanced by the presence of branches and roots, which help to anchor the debris and serve as a matrix to trap and consolidate sediment and fine particulate organic matter (Bisson et al. 1987; Gregory et al. 1991; Meehan and Murphy 1991). Large pieces of debris are generally able to store higher quantities of sediment and organic material than other kinds of structures, such as boulders or exposed root systems (Bisson et al. 1987). Smaller woody debris, such as branches, sticks, and twigs, which create sieve-like accumulations and are therefore the most efficient structures for retaining leaves (Gregory et al. 1991; Murphy and Meehan 1991), is also important. Thus, from a biological perspective, streams require complex arrays of different sizes of woody debris to maximize the benefits derived from organic matter retention (Gregory et al. 1991.) Organic matter stored by woody debris is considered to be a more important energy source for benthic invertebrates in streams than the wood itself, although certain invertebrates are specialized for processing raw wood (Bisson et al. 1987). As streams get larger, however, they retain less detritus because in general, retention structures, such as LWD, rapidly decline in abundance (Minshall et al. 1983).

However, on large rivers which contain anadromous salmonids, another important attribute of LWD and related roughness elements may come into play: the ability to trap and hold spawned-out salmon carcasses. Decomposing salmon carcasses are now recognized as an important source of marine-derived nutrients (MDN), which play a key role in the ecology of Pacific Northwest rivers (Gresh et al. 2000). MDN have been shown to be vital for the growth of juvenile salmonids (Bilby et al. 1996; Bilby el al. 1998). The nutrients in salmon carcasses are delivered in an organic form. Juvenile salmonids are thus able to utilize them both indirectly (increased algal growth and aquatic invertebrates) and directly through actual feeding on the carcasses (Gresh et al. 2000). Moreover, the presence of abundant carcasses in a stream can significantly increase the mean fork lengths of juveniles, and up to 40 percent of the carbon in salmon smolts can come from nutrients derived from decaying carcasses of the previous generation of salmon (Bilby et al. 1996).

Assuming the high potential importance of carcasses to juvenile salmonids, carcass distribution and availability within the river then become important issues. It is reasonable to assume that to achieve their maximum values (including for direct feeding by juvenile fish) carcasses would need to be both (a) deposited and held within rearing reaches, and (b) well-distributed throughout such reaches.

While no quantitative evidence exists, visual observations along the lower Sacramento River suggests that such carcass distribution attributes are clearly facilitated by the presence of LWD and other related roughness elements associated with natural, non-riprapped channels and river banks (*personal observation*, compiler). Riprap, on the other hand, has been shown to incise the adjacent thalweg and increase stream power, decrease near-shore roughness, and create a relatively smooth, hydraulically efficient surface along the rock blanket (*see* pages 7-8). These are clearly effects that would be counterproductive to efficient snagging and retention of carcasses, and hence optimal distribution of carcasses, for use by juvenile fish.

WOOD AS INVERTEBRATE HABITAT

Animal associations on woody debris in aquatic systems vary from those restricted to living on the wood to those using it only opportunistically. The sequence of colonists parallels the stage of wood decay (Sedell et al. 1988). New wood entering a stream is used primarily as habitat, colonized by a community of algae and microbes that in turn provides food for a group of insects called grazers or collectors. This type of feeding does not significantly affect the structure of the wood, but colonization of the superficial layer by fungi softens wood enough that it may be abraded and ingested by invertebrates that scrape their food off surfaces. Most important, however, the wood becomes suitable for obligate wood grazers and the more generalized wood shredders, such as caddisflies and stoneflies, which eat fungi-infested wood. These activities result in a sculptured surface texture that provides habitat for many organisms (Sedell et al. 1988).

Wood quality and texture help determine the kinds of organisms that will colonize a piece of wood. The species of wood, degree to which it is waterlogged, and decay class all affect the quality. The extent of colonization by terrestrial fungi and wood-boring insects also influences the attractiveness of the wood once it enters the water, because such activity is closely associated with decay class (Sedell et al. 1988).

Invertebrate production may be enhanced on LWD because of the complex array of micro-habitats for colonization and the retention of fine organic debris (Gurnell et al. 1995).

INPUT PROCESSES

The processes of transferring large pieces of wood from riparian forested areas to stream channels are: chronic–frequent inputs irregular in time and space; and episodic–infrequently spaced, often very large inputs (Sedell et al. 1988; Bisson et al. 1987). Chronic input processes include tree mortality from disease and insects combined with wind-throw or gradual stream undercutting of root systems. Episodic input processes include large-scale epidemics of insects or diseases, extensive blow-down, logging, debris avalanches, and massive erosion of river banks during flood events.

Much of the LWD inputs to streams thus consists of whole trees which fall in or near the stream. Woody debris may also be delivered from branches or crowns of trees which break off due to abrasion or other forces (Harmon et al. 1986). Models of such inputs have been developed and used to predict the number and volume of LWD pieces falling into a stream reach per unit of time (e.g., Van Sickle and Gregory 1990).

Such modeling has not yet been attempted for the Sacramento River. In fact, documented (published or unpublished) knowledge of LWD input processes, rates, and volumes for the reaches of the Sacramento River affected by bank protection, is completely lacking. However, some general assumptions about LWD input, by reach, are possible.

For Reach 3 (Ordbend to Colusa), where levees are set back and the river retains the most resemblance to natural functioning, significant wood input occurs due both to chronic and episodic occurrences. It appears that the major chronic process is gradual stream undercutting of root systems, whereas the major episodic process is massive river bank failures during floods. The relative degree of contribution by each type of process is unknown. But this reach of the river, because it has the smallest percentage of riprapped banks and thus the greatest annual sediment loss rate due to erosion (WET 1990, 1991), likely has the highest total rate of LWD input of the three impacted SRBPP reaches.

Within Reach 2 (Colusa to Verona) the river is generally much more highly constrained by levees that border the channel. This reach also has a greater percentage of banks that are riprapped, and thus less annual erosion than the uppermost reach (WET 1990, 1991). It appears that most erosion today in Reach 2 occurs along water-side berms that are not yet armored. Here, the major LWD input process is likely the chronic undercutting of tree root systems, although episodic bank loss events also still occasionally occur at scattered locations within the reach. Overall, total annual LWD input from within Reach 2 is likely intermediate between that of Reach 3 and Reach 1.

Reach 1, from Verona downstream to the San Joaquin River confluence, is clearly the most highly constrained by levees with rock armoring. Also, impacts of episodic flood events are greatly dampened compared to Reaches 2 and 3, because of both tidal action and the effects of several upstream flood bypasses and distributaries, both of which divert flows. Bank erosion rates in Reach 1 are thus relatively small (WET 1990, 1991). LWD input appears to result mainly from chronic events due to slow but steady under-cutting of roots. The major cause of today's erosion appears to be wind and vessel wave-wash; episodic massive bank failures are rare. The annual input rate of LWD is clearly quite small, and likely only a tiny fraction of the historical rate which occurred under pre-development conditions.

Within all three of the SRBPP impact reaches, there is one other annual wood input mechanism: orchard and levee maintenance pruning debris. However, such wood generally consists of only branches and twigs; rarely are whole trees or other forms of true LWD introduced. Such pruning debris is generally either (a) left in place where it falls, in which case it may be swept into the river during the next high flow, (b) dumped directly into the river, or (c) burned. However, due to air quality restrictions, burning of such debris has become less common than in the past. As with the various other mechanisms of wood input for the Sacramento River, debris inputted from pruning has never been quantified.

RETENTION CHARACTERISTICS

The location, stability, and longevity of LWD strongly influence fishery habitat quality in all sizes of streams, although the arrangement of woody debris varies according to stream size and valley morphology (Bisson et al. 1987). The spacing of individual debris pieces or clumps of pieces can be strongly influenced by dominant input processes. For example, when the dominant input is from bank undercutting of living trees or the direct fall of dead trees, debris tends to be spaced at fairly random intervals along smaller stream channels where discharge is insufficient to carry the debris pieces downstream. In most streams, however, there is some degree of clumping, and the magnitude and spacing of debris clumps generally increase in a downstream direction as the stream becomes larger. In intermediate and large streams, woody debris entrained by bank undercutting and direct fall is generally transported downstream during high flows and deposited on obstructions in the channel and on the outside of river bends near the high water line (Bisson et al. 1987).

Debris clumps that result from episodic inputs, such as massive bank failure during flood events, tend to be more widely spaced and the volume of the clumps greater than those observed in streams where this process is not important (Bisson et al. 1987). Following large flood events on the Sacramento River in 1986, 1997, and 1998, a number of new, large debris clumps appeared throughout Reaches 1-3 (*personal observation*, compiler).

Stable woody debris accumulations are important for maintaining good fish habitat (Sedell et al. 1988; Bisson et al. 1987). If debris moves less frequently, its functioning for food, habitat, and storage are increased over similar, but unstable accumulations (Bryant 1983). Size, including length, diameter, and overall mass, is a major determinant of debris stability (Bisson et al. 1987; Sedell et al. 1988; Lienkaemper and Swanson 1987). Stability is also determined by wood complexity. The more branches and roots which are intact on the wood piece, the more likely it is to snag securely on in-stream obstructions and to resist movement during flooding. Whole trees are thus generally much more stable than tree fragments (Bisson et al. 1987; Sedell et al. 1988). Large woody debris pieces tend to move into accumulations of smaller pieces and make them more stable than they would otherwise be in the absence of the large pieces (Lienkaemper and Swanson 1987). Large stable pieces also often maintain specific accumulation sites that last for decades (Swanson et al. 1976), and overall, they are most likely to make long-term contributions to habitat (Dolloff 1994).

In systems that have been undisturbed for a long time, LWD tends to exhibit a continual cycle of loss and replenishment. As some pieces are lost or moved about, new pieces take their place, preserving a state of dynamic stability (Dolloff 1994).

Other aspects of debris that influence stability include orientation, degree of burial, and the proportion of the piece that lies in water (Bisson et al. 1987; Sedell et al. 1988). Whether a piece of wood is buried depends on the sediment load in the channel. The degree of burial strongly influences debris movement; pieces with both ends anchored to the stream bed or bank move less than pieces with only one or neither end buried (Bilby 1984). Also, LWD with an angle of orientation relative to the axis of the flow of less than 30 degrees is much more stable than debris whose primary angle of orientation is greater than 60 degrees (Bryant 1983).

Although debris size, complexity, orientation, and degree of burial strongly influence whether a piece of wood moves or not, the spacing and amount of channel roughness elements influence the distances that pieces move (Young 1994; Lienkaemper and Swanson 1987).

Thus changes in near-shore or stream-flow characteristics often cause large and rapid changes to a stream's LWD retention and movement characteristics. For example, in a comparison between a burned and comparable, but unburned, stream in Wyoming, tagged debris in the burned stream moved over four times as fast as such debris in the unburned stream. Increased flows and decreased bank stability following the fire increased the transport rate (Young 1994).

Clearly, a substantial LWD transport rate increase would be expected in association with bank riprapping along the lower Sacramento River. Riprapping deepens the adjacent thalweg; removes natural roughness elements; creates a smooth, continuous hydraulic flow; increases velocities during flood events; and precludes firm anchoring of LWD into the soft streambed. In addition, during most bank protection work, any stable LWD along the shoreline is typically removed when the "toe" of the levee is reshaped prior to riprapping. As a result, today stable wood pieces along riprapped areas are rare; most remaining LWD of the lower Sacramento River, including the most stable pieces, clearly occur along the remaining non-riprapped banks (*personal observation*, compiler).

LONGEVITY

Woody debris can be extremely abundant in streams, even when the rate of input is relatively low, because it decays quite slowly (Bisson et al. 1987; Sedell et al. 1988; Murphy and Meehan 1991). The slow decomposition rate of wood in freshwater streams thereby maximizes its influence on stream stability and habitat value (Murphy and Meehan 1991). Woody debris decays slowly because of its high C:N ratio (Murphy and Meehan 1991) and waterlogging, which prevents deep penetration of oxygen into the wood (Sedell et al. 1988).

Waterlogged parts of fallen trees decompose in thin (0.25-inch) surface layers (Sedell et al. 1988). Because of their greater surface:volume ratio, branches and twigs decay faster than boles (Murphy and Meehan 1991). As the decomposed surface is grazed (by invertebrates) or abraded, oxygen penetrates farther into the wood, and that area becomes food for the decomposers. If only part of the wood is constantly in contact with water, that part decomposes slowly, but the exposed part may decompose rapidly because neither low oxygen nor extremes of moisture limit decomposer activity (Sedell et al. 1988).

LWD decay rates for the particular riparian tree species found along the lower Sacramento River have not been studied. However, in a study of streams in the southern Appalachian Mountains, the American chestnut tree was found to be a major component of total LWD mass, despite the fact that it had been unavailable for recruitment for decades (Hedman et al. 1996). In coniferous forests of the Pacific Northwest, dendrochronologic dating of debris in streams has documented pieces that have been in channels for 200 years or more (Bisson et al. 1987).

Because LWD can be so long-lived, even relatively small changes to the stream environment which reduce either the rate of wood input or its retention time can dramatically reduce its overall ecological values and functioning within the stream. Logging is one distinct source of change. For example, in a study of 17 streams in the Stanislaus National Forest of California, reaches within unmanaged coniferous forest had significantly more large wood and more stable large wood than reaches in second-growth stands (LWD was also less abundant overall than in the Pacific Northwest; Ruediger and Ward 1996).

A number of studies of streams in coniferous forests of the Pacific Northwest have demonstrated the dramatic declines of LWD functioning and values following logging of the watershed. For example, in a study in seven southeast Alaska watersheds, natural rates of input and depletion of LWD were studied to provide a basis for managing streamside zones to maintain LWD for fish habitat after timber harvest (Murphy and Koski 1989). Longevity of LWD was found to be directly related to tree or stem diameter: small (10-30 cm) LWD was less than 110 years old, whereas large (>60 cm) LWD was up to 226 years old. A model of changes in LWD after timber harvest showed that 90 years after clear-cut logging without a stream-side buffer strip, large LWD would still be reduced by 70 percent. Even more significant was the estimate of more than 250 years that would be needed to recover to pre-logging levels of LWD.

The dynamics of LWD on the Sacramento River may not follow exactly the same patterns as the coniferous forest examples. Yet there is at least one clearly parallel feature: clear-cut logging of coniferous forest removes trees, thereby halting natural LWD recruitment; similarly, riprapping of the lower Sacramento River removes trees (during bank reshaping prior to armoring) and halts natural LWD recruitment of remaining trees, by stopping erosion. This has a compounding effect, because *depletion* of instream LWD continues throughout any period of low or no recruitment, resulting in a net decline in LWD abundance for several decades, and sustained low amounts of LWD between 50 and 100 years after recruitment is affected (*in* Beechie and Sibley 1997).

In addition, bank protection clearly diminishes the ability of the river banks to capture and retain new wood, due to the uniformly smooth, hardened surfaces created both along the shoreline and along the bottom of the near-shore area. Thus, in both the coniferous forest and Sacramento River examples, the net result clearly is the same–a long-term decline of LWD in the stream.

Additional study, including modeling of LWD dynamics and declines along the lower Sacramento River, is needed. Such study could lead to better quantifying reach-specific impacts of bank protection, identifying the most debris-impoverished areas, and assessing the best options for restoration of the river's LWD functioning.

BIOMASS LOADING

As discussed earlier, little is known about either present or past biomass loadings of LWD in the lower Sacramento River. However, we do know that large numbers of snags (ave.=91/km) were removed from the river near the turn of the century (Sedell et al. 1990), suggestive of large LWD biomass loadings at that time. This inference is supported by the apparent high densities of near-shore LWD that can be seen in many historical photographs taken of the Sacramento River and vicinity before modern bank protection began, as well as in many older photographs of non-riprapped areas taken during the early stages of the modern bank protection era (*personal observations*, compiler).

For further inferences about the Sacramento River's historical LWD biomass loadings, we must look to results from other rivers. For example, in 11 riparian forest-stream systems in the southern Appalachian Mountains, loading volumes ranged from 7.1 to 31.2 m^3/100 m of stream, or between 3.6 and 13.2 kg/m^2 (Hedman et al. 1996). Another study reported LWD loadings of 52-85 kg/m^2 in coastal California redwood streams, 10-40 kg/m^2 in other coniferous forest streams in several states, and 3-9 kg/m^2 in several other widely scattered conifer and hardwood forest streams (Gurnell et al. 1995). However, these estimates generally involve higher-order streams than the lower Sacramento River. Relating them to the Sacramento River is thus somewhat problematic.

A downstream trend in the amount of LWD loading in the lower Sacramento River is likely, however, since this is a common feature of other large rivers (Gurnell et al. 1995). For example, a downstream increase up to sixth-order streams was reported in the low-gradient Ogeechee River environment in the southeastern U. S. (Benke and Wallace 1990). There too the major source of debris was from large trees falling into the river as a result of bank undercutting. Such large LWD rarely moved even in floods, because the extensive floodplain absorbed flood flows and buffered their velocities so that stream power was rarely sufficient to move it (Benke and Wallace 1990). Moreover, these stable wood pieces tended to capture additional wood, providing a further downstream increase in loading (Benke and Wallace 1990). A reasonable inference is that a similar situation may have previously existed for the lower Sacramento River, particularly under pristine, pre-development conditions, and perhaps more recently as well.

Also noteworthy is that studies have shown that LWD loadings are high in wide, sinuous valley-floor rivers (e.g., Nakamura and Swanson 1994). In addition, debris loadings often tend to increase linearly from mid-to late-successional stages through old-growth stages of riparian forest (Hedman et al. 1996). Thus, LWD loadings of the lower Sacramento River under former conditions may have approached or even greatly exceeded the maximum loading values reported above for other streams.

Clearly, however, to more accurately define the past and present woody debris loadings, and trends, for the lower Sacramento River, will require substantial additional study.

CUMULATIVE BANK PROTECTION

Since 1963, about 800,000 LF, or 152 miles, of riprapping has been completed under SRBPP authority. With construction soon of the remaining 6 miles (~34,000 LF) of second phase authorization, the total amount of river bank protected under SRBPP authority in the 194-mile-long project reach will increase from 35 percent (in 1987) to 41 percent (i.e., of 194 x 2=388 miles of banks) (USACOE 1987). The completed SRBPP will then encompass riprapping on about 44 percent of bank in the lower 60 miles downstream of Sacramento (i.e, RMs 0-60), 39 percent in mid-river between Sacramento and Colusa (i.e., RMs 60-145), and 30 percent between Colusa and Chico Landing (i.e., RMs 145-194) (USACOE 1987).

The SRBPP makes up only part of the total bank protection that has been completed within the project reach, however. Since 1963, riprapping has also been done by (a) various levee and reclamation districts, (b) private individuals, and (c) emergency (i.e., under auspices of Public Law 84-99) levee repair actions of the Corps in concert with local agencies. The total post-1963 non-project bank protection has not, to the best of the Service's knowledge, been quantified. However, for a preliminary[10] discussion of cumulative

[10]Non-project and pre-1963 bank protection estimates have been requested from the Corps as part of the Service's section 7, Endangered Species Act consultation for remaining proposed bank protection work. The assumptions and discussion herein will be adjusted accordingly, if necessary, when this information is received.

impacts, we assume the total non-project bank protection (since 1963) to be 10 percent of the completed SRBPP, or 16 miles. In addition, an unquantified amount of bank protection was placed within the project reach by various entities before 1963; until this amount is quantified, we estimate it as 15 percent (of completed SRBPP), or 24 miles. Thus, the estimated total riprap placed within the SRBPP reach is about 199 miles, or 51 percent of the 388 miles of river bank. The probable conservative nature of this estimate is illustrated by the Corps' estimate over 10 years ago that over 75 percent of the river bank downstream of Sacramento was already riprapped (USACOE 1987).

In addition to the SRBPP reach, another major Corps project–the Sacramento River, Chico Landing to Red Bluff Project–completed about 18 miles of riprapping within a 50-mile project reach, and another 15 miles of authorized work has been indefinitely delayed because of environmental concerns (USACOE 1994).

Of all previous bank protection applied along the lower Sacramento River, an unquantified amount has failed to some degree over time. Such failures range from minor displacements of rock armoring or earthen substrate to massive slippages of the levee structure. However, major failures are nearly always repaired. Minor failures, which may not be repaired, generally expose relatively minor amounts of earthen substrate. Therefore, the amount of levee erosion that has been restored (and which in turn could restore some ecological functioning) at previously riprapped sites because of riprap failures is assumed to be insignificant.

DISCUSSION AND CONCLUSIONS

Bank protection, as done along the lower Sacramento River under auspices of the Corps' SRBPP for the past 4 decades, has generally involved clearing (of vegetation) and grubbing (i.e., moving and/or adding soil and rock) to uniformly reshape the levee or bank, followed by riprapping the reshaped surface with river cobble stones (in the past) or quarry rock (today). Individual bank protection sites have generally ranged from a few hundred to a few thousand linear feet in length. Such bank protection generally results in two levels of impacts to the environment: Site-level impacts are impacts to the basic physical habitat structure at individual bank protection sites. Reach-level impacts are the cumulative impacts to ecosystem functions and processes that accrue from multiple bank protection sites within a given river reach.[11]

During the early years of the SRBPP, there was no compensatory mitigation provided for either site- or reach-level losses. Today, using the Service's HEP and various HSI models, including a model for SRA

Also, detailed mapping of all riprapped banks along the river will likely soon be undertaken as part of the Corps' Sacramento and San Joaquin Basins Comprehensive Study of flood control for major Central Valley rivers and tributaries.

[11]Here, reach means either one of the three reaches as defined on page 6, or a distinctly identifiable sub-reach within one of the three defined reaches.

Cover, the involved agencies are better quantifying and mitigating for the site-level impacts of bank protection. However, reach-level impacts are just beginning to be recognized and understood, and to date, there has been little, if any direct effort to provide specific compensatory mitigation for them.

Reach-level impacts arise primarily from halting erosion. Among the reach-level impacts which *may* in turn be causing significant impacts to fish and wildlife resources, depending on river reach, are: (a) reductions of new "accreted" habitats of various kinds, (b) changes to sediment and organic material storage and transport, and (c) reductions of lower food-chain production. Such impacts are extremely complex, however, and substantial additional study is needed to assess their biological significance relative to the lower Sacramento River.

On the other hand, extensive published and unpublished evidence already exists to conclude that another reach-level impact of bank protection–reduction of LWD functioning–is both large and important relative to the lower Sacramento River. LWD and other forms of in-stream wood are widely important to ecological processes and functions in streams and rivers or all sizes across all kinds of environments. And LWD is particularly important to fishes, including juvenile salmonids and other species, many of which are now federally listed.

As with other ecosystems impacts, impacts to LWD functioning are largely related to rock armoring effectively stopping erosion. Absent erosion, *recruitment* of new LWD to the river from tree root undercutting or massive bank failure is halted. In addition, since most riprapping involves first clearing and grubbing to reshape the bank, most, if not all of the existing, often mature, riparian vegetation is frequently removed. This further decreases, if not eliminates, potential of any future wood recruitment to the river from the riprapped site.

Compensatory mitigation efforts for site-level riparian vegetation losses sometimes result in new vegetation being established within or upslope of newly riprapped areas (where permitted by levee maintenance guidelines). However, since erosion has been halted and the replacement vegetation is early successional stage which is invariably farther from the shoreline, only minimal LWD recruitment can ever be expected. Recruitment is limited to any eventual, long-term tree mortality (i.e., insects, fire, disease, and decadence) and whatever abrasion and breakage may occur during high flows.

Rock armoring also greatly reduces, if not eliminates, the *retention* of LWD which is inputted from the lower Sacramento River's limited remaining recruitment sources (i.e., non-riprapped areas, either within the project reach or upstream). Riprapping creates a relatively clean, smooth, and featureless surface which diminishes the ability of LWD to become securely snagged and eventually well-anchored by sediment. Wood tends to become only temporarily snagged along riprap, and generally moves downstream with subsequent high flows. Habitat value and ecological functioning aspects are thus greatly reduced, because wood needs to remain in place to generate maximum values.

Clearly, the result for the lower Sacramento River is that new wood has not been replacing old, in-stream LWD that is gradually re-entrained and transported downstream during major flooding events. Thus, any equilibrium with respect to LWD, assuming one existed in the post-settlement, pre-riprapping era, has been upset and a downward trend for LWD has likely existed for at least several decades. Moreover, because LWD can be so long-lived under unimpaired conditions, often functioning for over a hundred years, the cumulative loss of LWD *functioning* as a result of bank protection is no doubt much larger than the 51 percent of river banks which have now been riprapped. Acting in a synergistic fashion, the loss of at least one-half of both LWD *recruitment* and LWD *retention* has likely resulted in a loss of two-thirds or more of LWD *functioning* (compared to pre-SRBPP conditions) overall for the lower Sacramento River. And within the lowermost river reach where riprapping is most extensive (i.e., over 75 percent of banks), the loss of LWD functioning may now easily exceed 90 percent.

Consequently, all or portions of the lower Sacramento River may now be significantly debris-impoverished to the extent fish populations are ultimately being directly impacted. In particular, Sacramento splittail may be impacted by the reductions of their critical spawning substrates and juvenile rearing habitat associated with the losses of LWD. Splittail probably rely almost exclusively on near-shore LWD and associated SRA Cover and natural bank areas during drier years in which flood bypass flows are low or nonexistent. Juvenile salmonids may be similarly impacted by reductions of rearing habitat as well as the serious fragmentation and general lack of connectedness of remaining near-shore, LWD-associated refugia areas. Any further incremental, cumulative loss of LWD functioning within *any* of the three river reaches should therefore be considered a serious and unacceptable impact.

The extent of the problem can be visually observed simply by driving an automobile along some of the river's levees. Numerous river segments can be observed, some many miles in length, where both opposing river banks are totally riprapped and completely devoid of either riparian vegetation or any near-shore LWD. Even if a mitigation strategy can be devised and implemented to begin to correct such refugia voids, it may require decades–if not hundreds of years–to overcome the serious fragmentation and general lack of input, retention, and functioning of LWD that exists today.

The Sacramento River is thus like most other large rivers of the West and Pacific Northwest. There has been a universal trend toward fragmentation and disconnection from important river processes and functions. While there are many sources for such disconnect, including dams, diversions, changes in flow regimes, and levees built too close to the river, modern bank riprapping efforts have clearly been an important cause of general ecological decline.

Maintenance of biotic diversity and natural community dynamics in streams and rivers is directly related to the preservation of natural habitats and associated processes within the basin (Sedell et al. 1990).

Moreover, the greatest diversity and aerial extent of riverine refugia[12] occur where there is a maximum interaction between floodplain and aquatic systems (Sedell et al. 1990). In general, more complex units and channels are more likely to serve as refugia than less complex ones (Sedell et al. 1990).

Another consequence of long-term bank protection has been the general simplification of fish habitat. Simplification includes a decrease in the range and variety of hydraulic conditions, reduction in the amount of LWD and other structural elements, and a decrease in the frequency and diversity of habitat units and substrate types (Reeves and Sedell 1992). Such simplification has clearly been one of the effects of extensive riprapping of the lower Sacramento River.

To begin restoring habitat complexity and reversing other long-term reach-level losses requires among other things, that we begin avoiding bank protection impacts in the first place. Impact avoidance can be achieved using set-back levees (i.e., new levees built landward of the existing levees) in various strategies to achieve bank protection goals. Set-back levees allow avoidance of both site-and reach-level impacts, including impacts to LWD functioning, and often create considerable opportunity for habitat and ecosystems functioning enhancement.

At specific sites where avoidance of impacts to SRA Cover and ecosystems functioning elements is truly infeasible (e.g., where the existence of significant infrastructure would make a set-back levee cost prohibitive), factors contributing to reach-level impacts should nonetheless be quantified to the extent possible, and appropriate compensatory mitigation measures should be developed and employed, just as is currently done for site-level impacts. An ecosystems model for the river (or appropriate modifications of the Service's existing SRA Cover model) is needed for such impacts and compensatory mitigation analyses. Development of such a model should receive highest priority.

In the interim, one useful approach could be to address reach-level ecosystem impacts using a habitat-value-based analysis in which (a) the estimated erosion rate (e.g., feet/year) of a site times the site length is used as a measure of ecosystems functioning *area,* and (b) the types and amounts of substrate and riparian vegetation present (and thus subject to erosion) are used as a measure of *value* (i.e., a HSI). The product of this area and value (i.e., Habitat Units of *ecosystems functioning*), could then be used in a traditional HEP accounting process.

When no other recourse exists except but to attempt to physically *replace* pieces of LWD impacted by riprapping, careful design of the mitigation is essential. Especially where the burying or attachment of replacement wood to riprapped surfaces is involved, planners must ensure that the replacement wood feature is (a) either designed to last the full life of the bank protection work, or will be maintained and

[12] Sedell et al. 1990, define refugia as habitats or environmental factors that convey spatial and temporal resistance and/or resilience to biotic communities that have been impacted by biophysical disturbances.

replaced as needed during that life, and (b) designed to replace the full range of ecological values and functions of the impacted wood. Both objectives will generally be facilitated by the use of large, complex wood pieces (e.g., LWD as defined in footnote 6 on page 8).

Compensatory mitigation approaches must also be developed and implemented to offset the loss of wood retention caused by riprapping. Some possible options for restoring "roughness" elements to riprap to facilitate wood retention include: (a) scalloping the shoreline, (b) constructing groins, weirs, wing dams, benches or other kinds of uneven surfaces, (c) using boulders as part of the rock protection, or (d) having pilings or other structures protruding above the rock surface.

Mitigating for losses of wood functioning will also require an understanding of the volumes, numbers, and distributions of wood input, before and after bank armoring, both for individual bank protection sites and affected river reaches. Analyses could begin with studies of historical photographs and actual on-the-river surveys, facilitated by a computerized geographic information system (GIS). This in turn could facilitate development of a LWD functions model, either separately, or as part of a more comprehensive river ecosystems model.

Finally, this discussion is concluded by proposing that the functioning of LWD in the lower Sacramento River should be viewed as the equivalent of the legendary canary in the gold mine. The canary was used to signal the ability of a mine to support life. The relative amount of natural LWD functioning provides a similar measure for the river. Moreover, the degree to which such functioning is increased and restored will be directly proportional to the degree to which *all* of the lower river's ecological functions and processes can be and are eventually restored.

RECOMMENDATIONS

Based on the discussions herein, the Service considers several goals, objectives, and actions to be both warranted and prudent for the lower Sacramento River, including:

- Ensuring no further incremental losses of ecoystem functioning due to ongoing and future bank protection within *any* of the three impacted lower river reaches;

- Redoubling efforts to implement set-back levee approaches for ongoing and future bank protection, so as to maximize avoidance of *all* site- and reach-level impacts, while creating significant habitat and ecosystems rehabilitation opportunities;

- Refining the preliminary estimates herein, through analyses of historical photographs, ground surveys, and other means including modeling, of (a) present LWD status (including input and retention); and (b) the LWD functioning losses that have resulted from cumulative past bank protection;

- Conducting additional studies to specifically identify the most LWD-impoverished sites along the river, within each reach, where rehabilitation should be directed;

- Conducting additional studies, focusing in Reaches 1 and 2 (in that order), of the importance of SRA Cover and LWD to juvenile salmonids, Sacramento splittail, and other native fishes;

- Developing an ecosystems functions model for the lower river–or appropriately modifying the Service's existing SRA Cover model–for use in impacts analyses and compensatory mitigation development, so as to address *all* site- and reach-level impacts;

- Developing and implementing appropriate compensatory mitigation strategies for future losses of LWD functioning where set-back levees are infeasible, which ensure: (a) replacement of *all* the attributes of LWD functioning, (b) the re-creation of lost LWD capture and retention characteristics, and (c) the full functioning of any installed mitigation feature(s) for the engineering design life of the bank protection work;

- Developing and implementing appropriate major, long-term rehabilitation strategies, which focus on elimination of the most seriously impacted areas from an ecosystems functioning perspective, and ensure the restoration of critical habitat continuity and refugia distribution; and

- Coordinating closely all of the above actions with the programs and specific actions of both CALFED and the CVPIA, which are directing hundreds of millions of dollars into Central Valley and Delta ecological restoration efforts.

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